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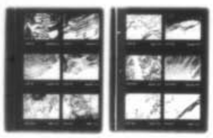

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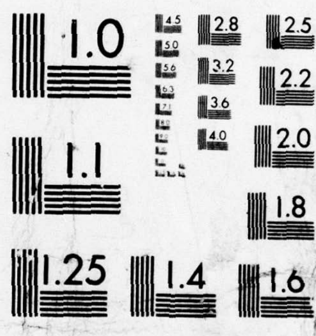

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METALLURGICAL CHANGES IN THE HIGH TEMPERATURE FRETTING OF Ni and Ti ALLOYS

Second Technical Report

by

R.B. Waterhouse

October 1977

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Ti-6Al-4V specimens subjected to fretting fatigue at 400°C have been examined in SEM. Layer formation similar to that obtained on specimens tested at 200° and 600°C was observed. Fatigue and fretting fatigue curves have been determined on Inconel 718 at 20°, 280°, and 540°C, together with isolated observations at 700°C where creep becomes excessive. Raising the temperature has little effect on fatigue strength but improves the fretting fatigue strength. The improvement is thought to be due to glaze formation.

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Summary

Ti-6Al-4V specimens subjected to fretting fatigue at 400°C have been examined in SEM. Layer formation similar to that obtained on specimens tested at 200° and 600°C was observed. Fatigue and fretting fatigue curves have been determined on Inconel 718 at 20°, 280°, and 540°C, together with isolated observations at 700°C where creep becomes excessive. Raising the temperature has little effect on fatigue strength but improves the fretting fatigue strength. The improvement is thought to be due to glaze formation.

Introduction

In the First Technical Report, October 1976, the construction and operation of an experimental rig for testing the fretting fatigue behaviour of two materials used in gas turbines was described. Preliminary experiments were carried out on the alloy Ti-6Al-4V obtained from IMI to prove the apparatus before embarking on tests on the materials supplied by AMMRC. The results of these preliminary tests were reported in the Second Periodic Status Report, March 1977, and showed that raising the temperature to 400°C had little effect on the fretting fatigue strength at 10^7 cycles (85 MN/m^2). At 600°C the fretting fatigue strength was reduced to 62 MN/m^2, compared with a fatigue strength in the absence of fretting at this temperature of 125 MN/m^2. However, it was pointed out that this alloy would not be expected to operate at a temperature as high as this. At higher stresses the fretting fatigue life was successively reduced as the temperature was raised. The conclusion from this investigation is that at the temperature which the alloy is likely to operate as specified by AMMRC, namely 100°C, there is little difference in the fretting fatigue properties with those at room temperature.

Scanning electron microscope (SEM) examination of fretted surfaces showed that layered structures developed at 200°C and these were more marked at 600°C developing into elephant trunk growths. Examination has now been made of the specimens tested at 400°C and they are described below.

SEM examination of Ti-6Al-4V (IMI 318) specimens subjected to fretting fatigue at 400°C

All the fretting scars on the specimens and bridge feet were examined after failure in the SEM. The following typical examples have been chosen for comment. The specimens were tested at a mean stress of 247 MN/m^2 and the stated alternating stress. The clamping pressure was 32 MN/m^2. The number of cycles to failure is given.

Specimen S44   ±170 MN/m^2 118,000 cycles

Plate I shows a fatigue crack in material transferred from the bridge foot to the specimen. This crack propagated out of the fretted region.

Specimen S42   ±154 MN/m^2 137,100 cycles

Plate II shows a deep depression made by the reciprocating motion of a large particle which has eventually become detached (see

Plate VI).

Plate III shows the break up of material transferred from the bridge foot. X-ray dispersive analysis indicates that the Al content of the transferred material is lower than that of the original surface.

Specimen S43 ±124 MN/m^2 183,200 cycles

Plate IV shows a fatigue crack in transferred material. This crack propagated out of the fretted region.

Plate V shows evidence of the transferred material being made up of multiple layers. As in the previous case the Al content of the transferred material was lower than that of the original surface.

Specimen S32 ±108 MN/m^2 222,000 cycles

Plate VI shows a large particle which has been pushed backwards and forwards in the transferred material and will eventually become detached.

Plate VII shows an oblique view of transferred material and demonstrates its layer structure.

Specimen S45 ±93 MN/m^2 749,100 cycles

Plate VIII shows what is thought to be the early development of the layer structure in transferred material.

Plate IX shows a later stage with the development of a large protuberance. The reciprocating action of such built-up material is thought to result in the formation of the type of particle shown in Plate VI which, on becoming detached, leaves depressions similar to that shown in Plate II.

Specimen S41 ±93 MN/m^2 8,814,200 cycles

Plate X shows the removal of material by delamination, its displacement, and its reattachment which constitutes the initial stages of layer formation.

Specimen S30 ±77 MN/m^2 10,998,100 cycles

Plate XI shows a dumbbell shaped depression where delamination has occurred within a region of transferred material.

Plate XII shows the break up by delamination of transferred material.

The SEM examination indicates that material is transferred from the bridge foot to the specimen surface. The fretting action causes displacement of material by a partial delamination process or by complete delamination and reattachment to give the ridged structure evident in Plate VIII and previously observed (see Fig 5, First Technical Report, October 1976). By further slippage of the layers over one another the multilayered structure shown in Plates VII and IX is formed. The reciprocating action then results in the partial detachment of this material, Plate VI, and eventual complete removal. Additional fatigue cracks are only observed at the higher alternating stresses.

Fretting fatigue of Inconel 718 at elevated temperatures

Fatigue curves have been determined on aged Inconel 718 with and without fretting under the following stressing conditions:

mean stress	550 MN/m^2
clamping stress	32 MN/m^2

at 20°, 280° and 540°C. Creep of the specimens at 700°C rendered a complete curve impossible to determine at this temperature. The results are shown in the graph. Although the fatigue results in the absence of fretting show considerable scatter it appears that they belong to one population giving a fatigue strength at 10^7 cycles of 550 ±320 MN/m^2. In the presence of fretting the results are much less scattered. Fretting at 20°C and 280°C reduces the fatigue strength at 10^7 cycles to 550 ±120 MN/m^2. However, at stresses above this the life at 280°C is approximately an order of magnitude greater than the life at 20°C. At 540°C the fatigue strength at 10^7 cycles rises to 550 ±250 MN/m^2. At higher stresses the fatigue life falls dramatically and is comparable with the strength at 20°C. It is thought that creep may be contributing to the failure process at these higher stresses.

SEM examination of Inconel 718 specimens subjected to fretting fatigue at elevated temperatures

The photographs shown below are a small selection from the extensive examination of all the failed specimens.

Specimen 97 20°C ±260 MN/m^2 131,000 cycles

Plate XIII shows a layered structure similar to that seen in the titanium alloy.

Plate XIV shows evidence of delamination and incipient cracks.

Plate XV is of a site adjacent to the fracture and shows transferred material and delamination.

Specimen 100 20°C 550 ±120 MN/m^2 10,228,100 cycles

Plate XVI shows the specimen surface immediately adjacent to the fracture. There is evidence of secondary cracking and delamination.

Plate XVII is an enlarged view of part of the same field in the previous plate showing removal of material by delamination apparently with the formation of numerous hair-line cracks. The chemical composition of the delaminating layer and the underlying material is identical.

Specimen 103 280°C ±260 MN/m^2 1,781,800 cycles

Plate XVIII shows a large block of material transferred from the bridge foot.

Plate XIX shows smaller regular accretions of transferred material.

Plate XX shows a surface structure arising from plastic deformation which suggests the rotation of blocks of material. At the bottom of the picture it gives the appearance of twinning. The similarity

between this structure and the transferred material of Plate XIX suggests that the latter may be individually transferred blocks of rotated material.

<u>Specimen 121</u> 280°C ±143 MN/m^2 4,637,100 cycles

Plate XXI shows the edge of the fracture and a subsidiary parallel crack. Widely distributed transferred material is evident.

Plate XXII shows another part of the edge of the fracture with a major subsidiary crack with numerous minor cracks.

<u>Specimen 95</u> 540°C ±290 MN/m^2 243,100 cycles

Plate XXIII shows plastically deformed transferred material developing into a multilayered structure.

<u>Specimen 102</u> 540°C ±250 MN/m^2 8,820,800 cycles (unbroken)

Plate XXIV shows a large particle about to become detached.

Plate XXV is an enlargement of the centre of the particle showing that it is made up of severely deformed material containing numerous cracks.

Plate XXVI is a view of the scar on the bridge foot which was in contact with this specimen. Massive transfer of material from the pit (to the right) to the pile (to the left).

Plate XXVII is also of the bridge foot and shows areas of severe deformation separated by smooth areas where smooth sliding or smearing has occurred.

<u>Specimen 119</u> 700°C ±228 MN/m^2 4,180,000 cycles

Plate XXVIII shows the edge of the fracture. Delamination of smeared material is evident adjacent to the fracture.

Plate XXIX shows the formation of a system of regular parallel cracks in transferred material.

Plate XXX shows the development of facets in transferred material.

To sum up the observations at the four temperatures:

at 20°C the emphasis is on subsidiary cracking and delamination with some layer formation;

at 280°C massive transfer of material from the bridge foot to the specimen occurs and there is evidence of the development of regular deformation structures;

at 540°C considerable plastic deformation is apparent and the formation of large particles of very disorganised material. There are, however, areas where there appears to have been smooth sliding which may indicate glaze formation;

at 700°C large smooth areas are visible suggesting glaze formation but the development of multiple cracks and facetted surfaces is thought to be due to the influence of creep.

The two observations which require explanation are (a) the longer fatigue life at higher stresses at 280°C compared with 20°C, and (b) the improved fatigue strength at 10^7 cycles at 540°C. Multiple cracking and delamination appears more prevalent at 20°C and may be the reason for the earlier initiation of a propagating fatigue crack. Massive transfer of material and evident plastic deformation does not appear a deleterious factor at 280°C. At 540°C the appearance of plastic deformation and glaze formation is the predominant feature and is thought to be the overriding beneficial effect, although at higher stresses there is the possibility of creep contributing to the failure mechanism.

In the case of the titanium specimens delamination and multilayer formation is a feature at all the test temperatures.

Conclusions

The observations of Ti-6Al-4V specimens fretted at 400°C suggest that the type of damage is intermediate between that at 200°C and 600°C. Multiple layers of transferred material are evident but not to such a great extent as at the higher temperature. It is suggested that multilayer formation and delamination are associated with low fatigue strength, since this is also found in Inconel 718 tested at 20°C. Surface plastic deformation and glaze formation which occurs on Inconel 718 at 540°C contributes to its improved fretting fatigue strength.

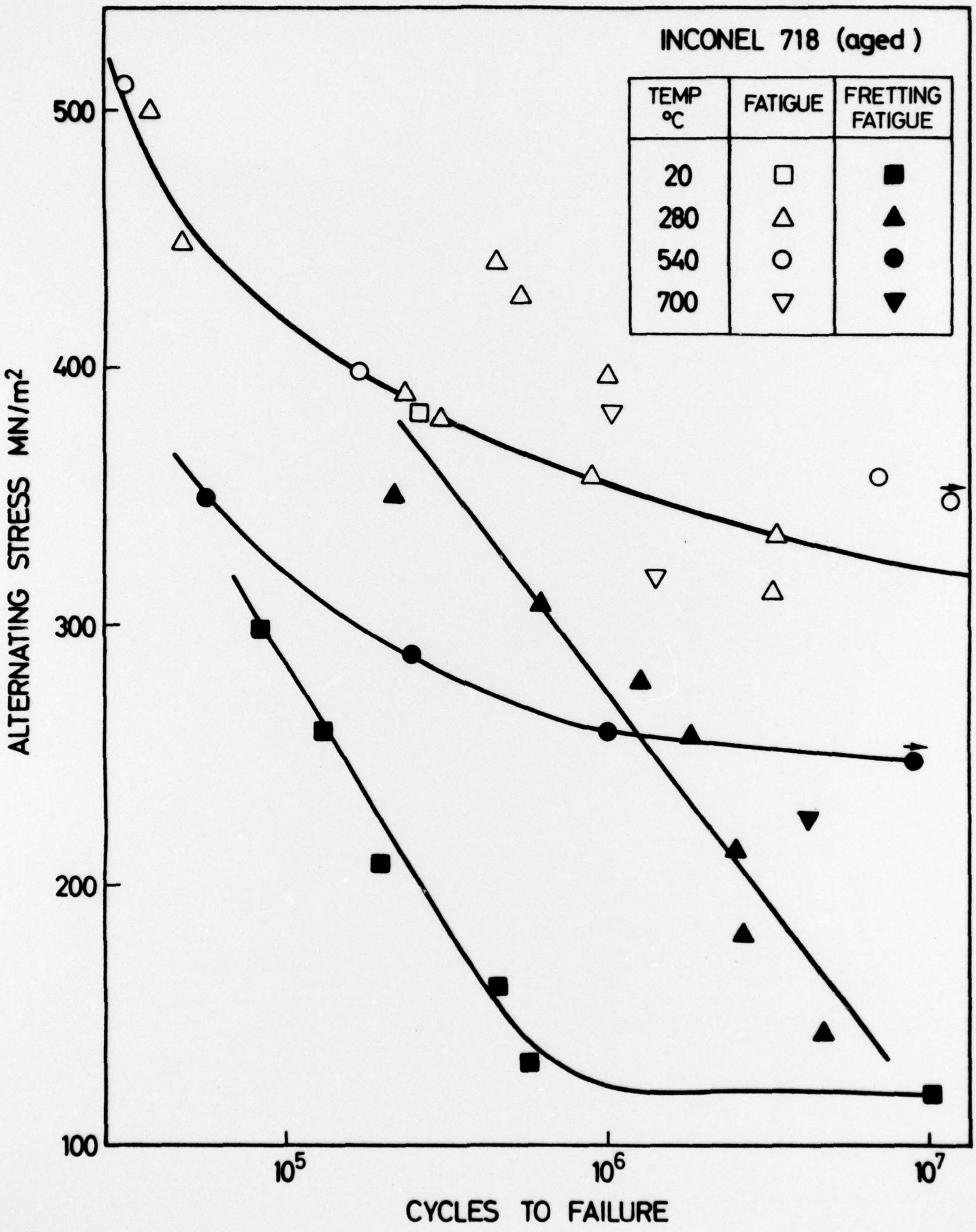
Future work

The Ti-6Al-4V material supplied by AMMRC has yet to be tested at 20°C and 100°C. The early stages of fretting damage in all the materials at all the test temperatures has to be studied. Sectioning and microscope examination of all specimens has yet to be undertaken. Thinning of selected specimens for examination in the TEM will be carried out in order to elucidate some of the surface structures that have been observed.

Appendix

Mechanical Properties of Aged Inconel 718

UTS	1316 MN/m^2
0.2% PS	1072 MN/m^2
Elongation	15.5%
Reduction in area	40%
Hardness	450 VHN



INCONEL 718 (aged)
TEMP °C
FATIGUE
FRETTING FATIGUE
20
280
540
700
ALTERNATING STRESS MN/m²
500
400
300
200
100
10⁵
10⁶
10⁷
CYCLES TO FAILURE

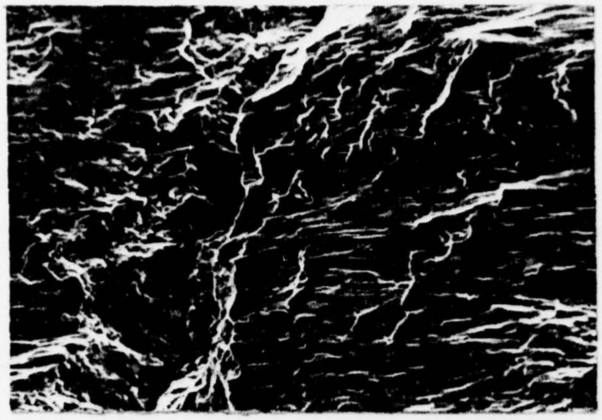


PLATE I — 40 μ

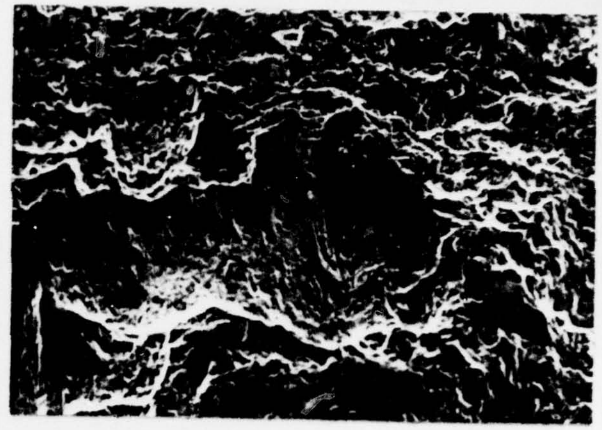


PLATE II — 40 μ

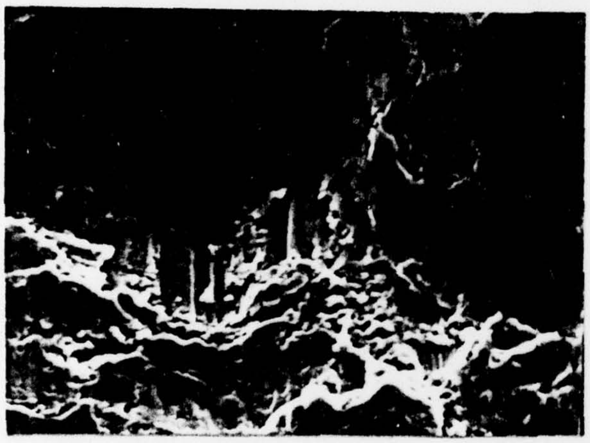


PLATE III — 10 μ

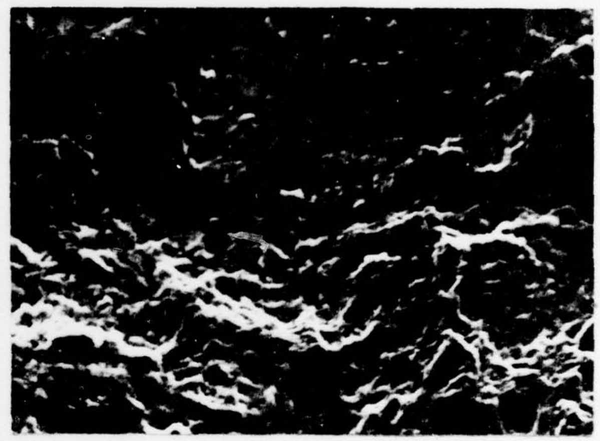


PLATE IV — 10 μ

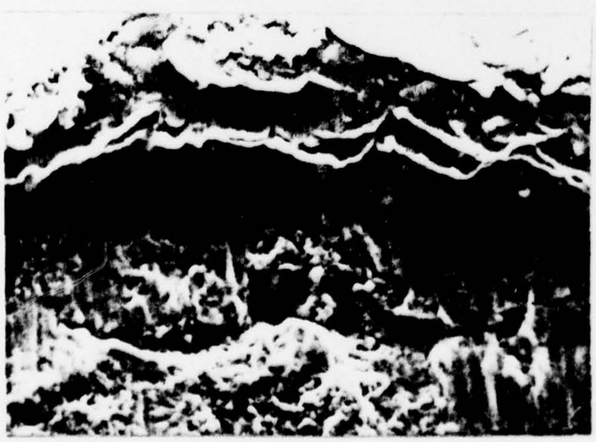


PLATE V — 10 μ

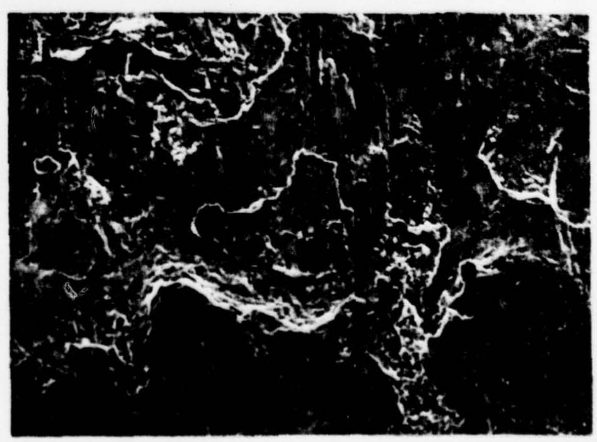


PLATE VI — 40 μ

PLATE VII 10 μ

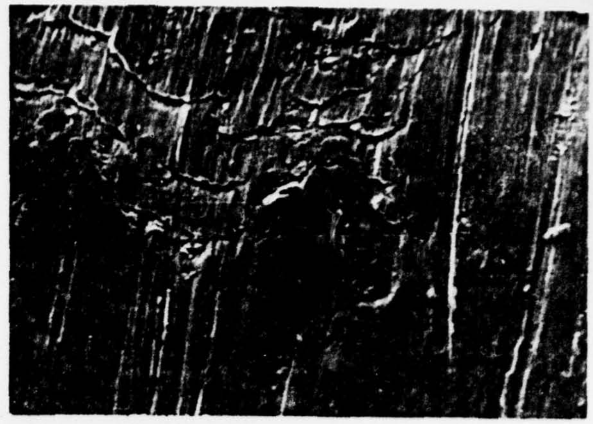


PLATE VIII 40 μ

PLATE IX 40 μ

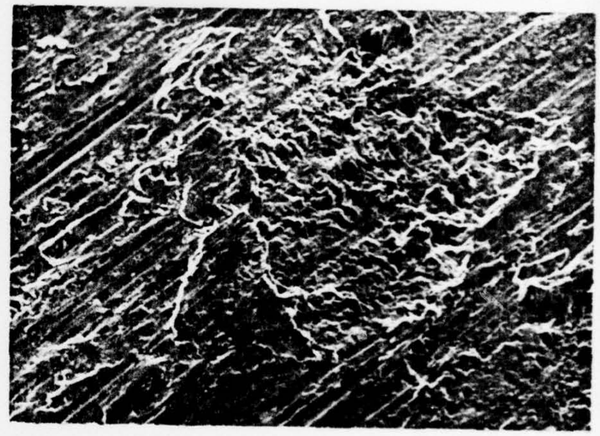


PLATE X 40 μ

PLATE XI 100 μ

PLATE XII 10 μ

PLATE XIII 10 μ

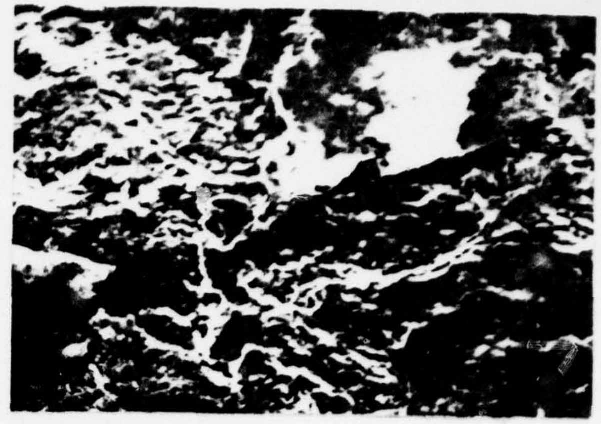


PLATE XIV 10 μ

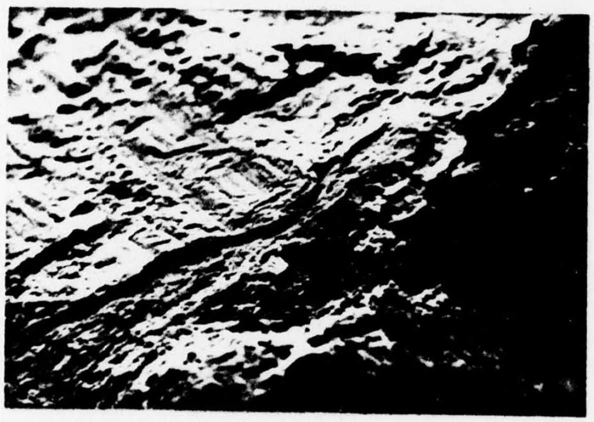


PLATE XV 40 μ

PLATE XVI 40 μ

PLATE XVII 10 μ

PLATE XVIII 100 μ

PLATE XIX 10 μ

PLATE XX 4 μ

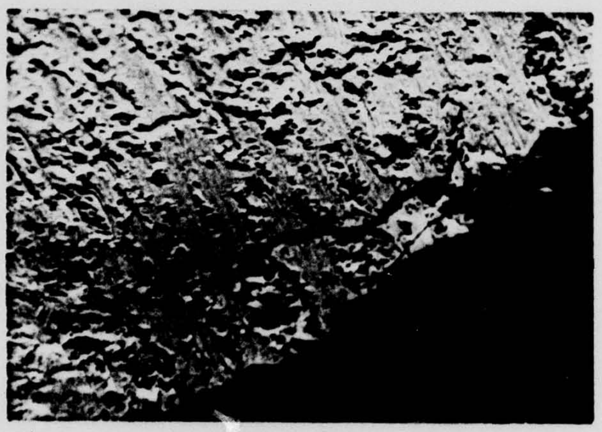


PLATE XXI 40 μ

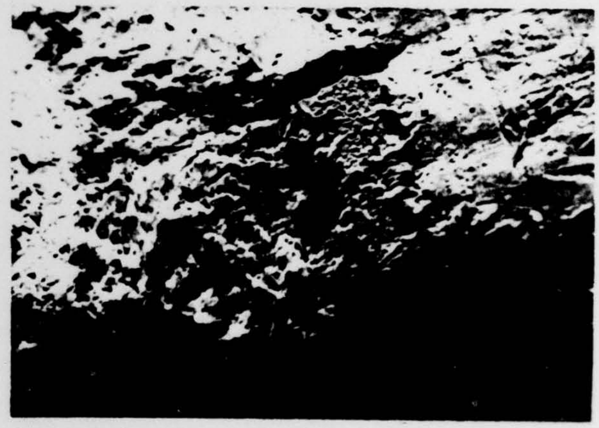


PLATE XXII 40 μ

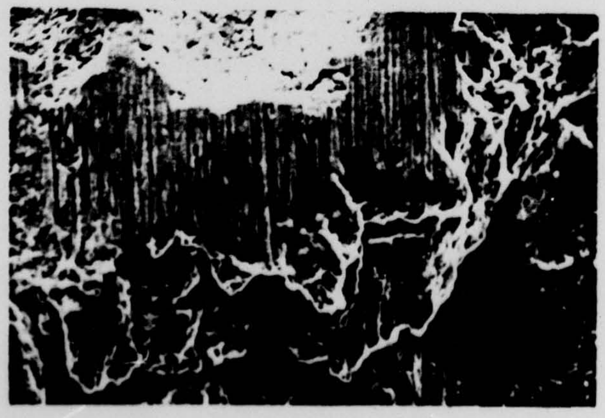


PLATE XXIII 10 μ

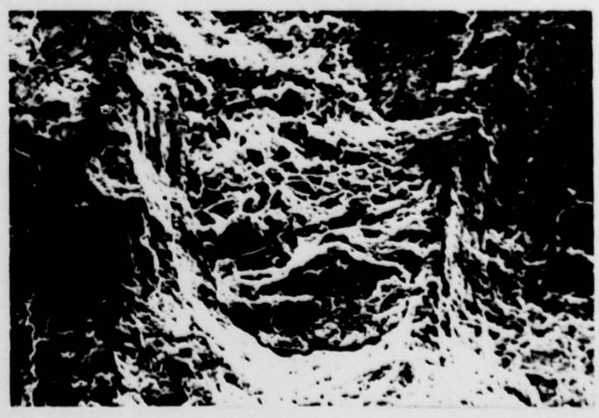


PLATE XXIV 40 μ

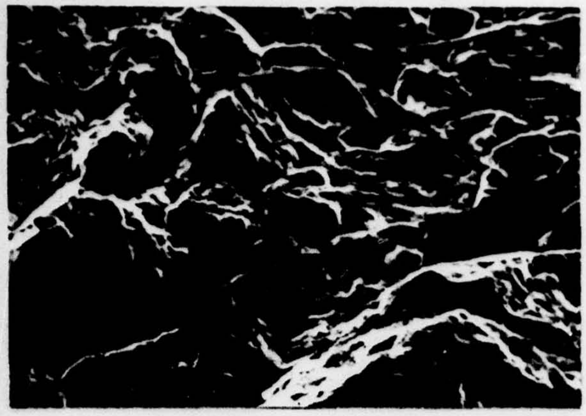


PLATE XXV 10 μ

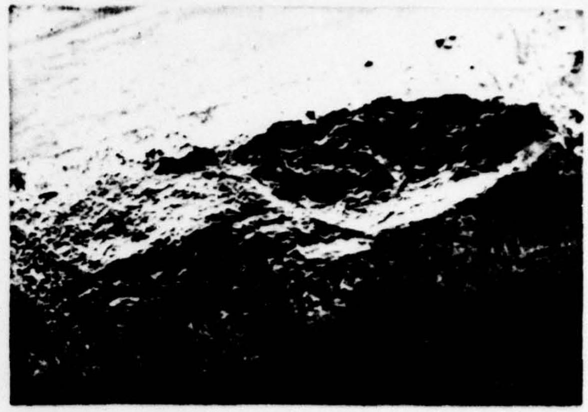


PLATE XXVI 400 μ

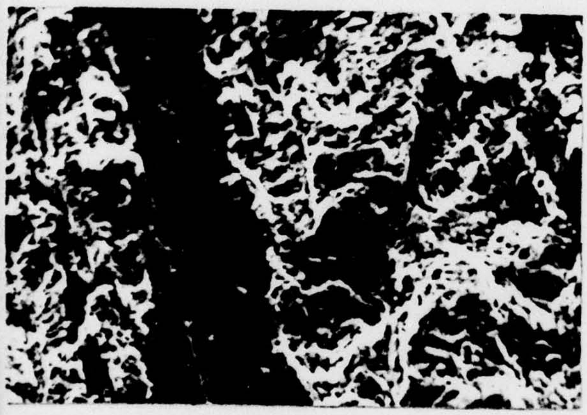


PLATE XXVII 10 μ

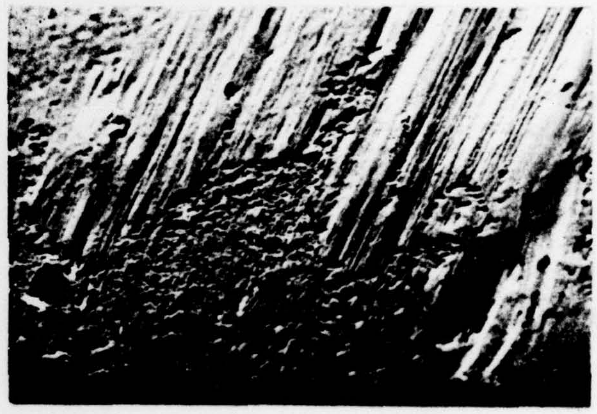


PLATE XXVIII 100 μ

PLATE XXIX 40 μ

PLATE XXX 10 μ